Real-time Performance and Scalability at the Expense of Consistency in LVC Simulations: A Fundamental Trade

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ITEA LVC Conference Jan 12-15, 2009

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JAN 2009**	2. REPORT TYPE	3. DATES COVERED **00-00-2009 to 00-00-2009**
4. TITLE AND SUBTITLE **Real-time Performance and Scalability at the Expense of Consistency in LVC Simulations: A Fundamental Trade**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **ASC/XRA,Simulation & Analysis Facility,Wright Patterson AFB,OH,45433**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**16**	

Standard Form 298 (Rev. 8-98)
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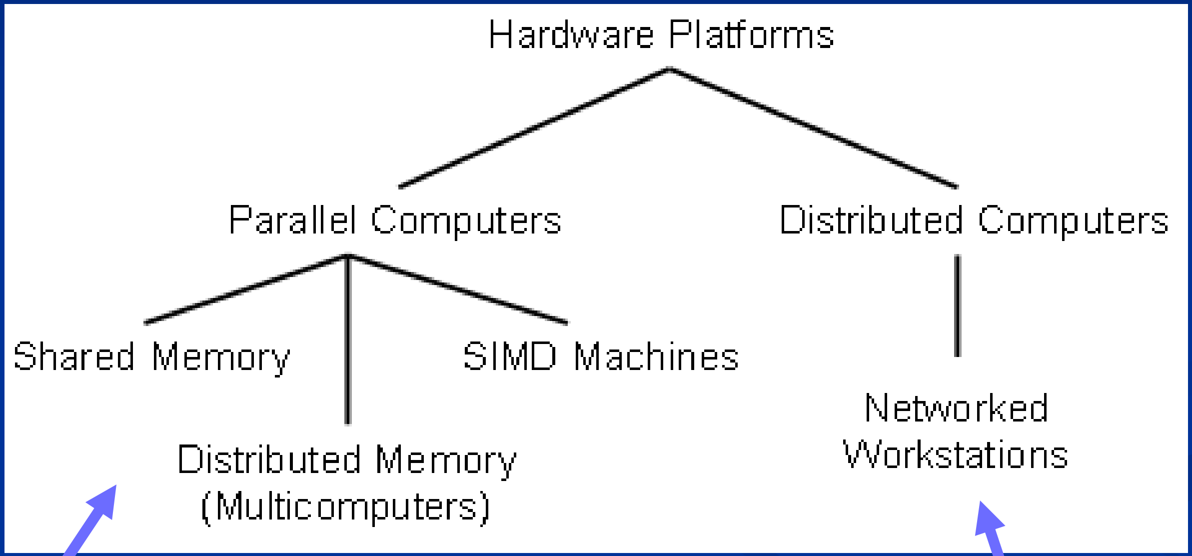
Two Worlds

- Analytic Simulations
  - Execution: Typically As-Fast-As-Possible
  - Objective: Quantitative Analysis of Complex Systems
  - Human or System Hardware Interactions: None
- LVC Simulations
  - Execution: Distributed Real-time
  - Objectives: Training, Human Factor Studies & Strategy Evaluation
  - Human or System Hardware Interactions: People and/or Hardware Integral to Controlling the Behavior of Entities

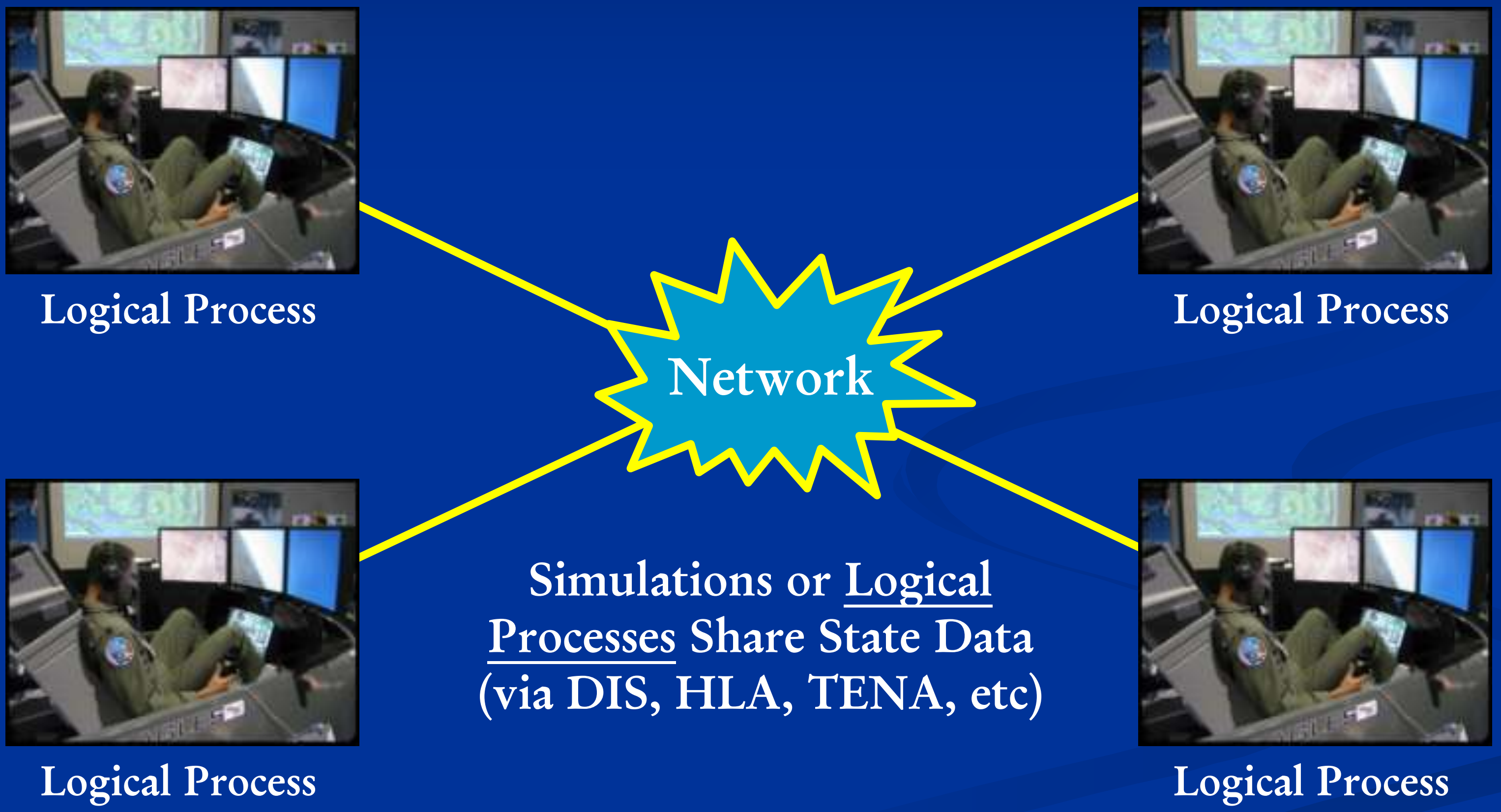
Hardware Topologies



Analytic Simulations
Typically Use Low Latency Interconnects

LVC Simulations
Typically Use Relatively High Latency Interconnects (5-100ms or More)

Anatomy of an LVC Simulation

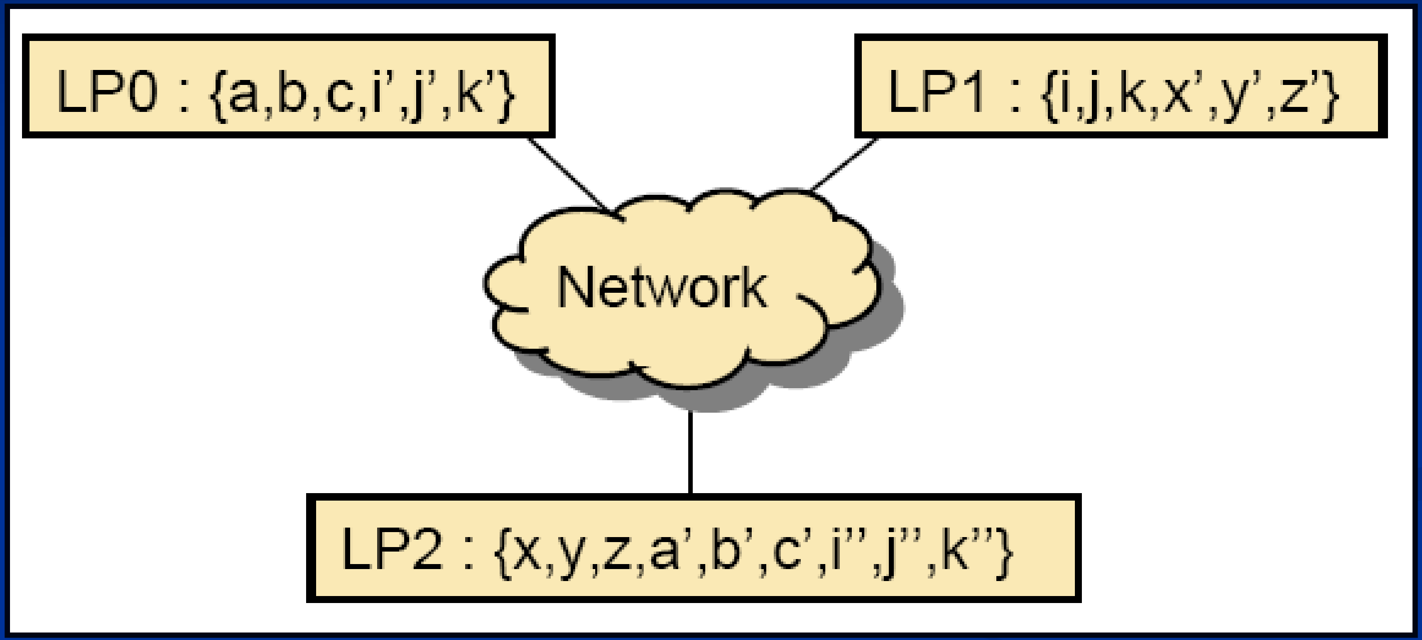


Characteristic	Requirement or Result
Human and/or System Hardware in-the-Loop	Real-time Response and Execution
	Fundamental Conflict!
Geographically Distributed Systems	Relatively High Latency to Move Shared Data

Fundamental Conflict

- Logical Processes
  - Require State Data that is Not Locally Managed to Produce Correct Outputs
  - Cannot Wait for the Most Current Value and Still Meet Interactive Response Time Requirements
  - Must Advance Time with Wall-clock (i.e., Real-time)
  - If Network Exhibits a Relatively High Latency, Data Transmitted by One Logical Processes Might be Inconsistent and "Old" by the Time it's Received by Another
- Distinguishing Characteristic of LVC Simulations
  - Inconsistency in Shared State Data
  - Value of Distributed Data Objects are Not Equal

Distributed State Space (Data)



- Each Logical Process (LP0, LP1 and LP2) Locally Manages Part of the Simulation State Space (Data), While Replicating Others

Performance/Scalability

- Relaxing <u>Absolute</u> Data Consistency Improves
  - Performance
    - Measure: Interaction Response Time
  - Scalability
    - Measure: More Logical Processes from More Distant Geographic Locations can be Connected

Measuring Inconsistency

- Measured in Terms of Age
  - Time Since Data Object Last Computed by
    - A System Model (Ex: Updating the Position of Aircraft)
    - Sampled from the Real World (Ex: Value Sampled by a Real Sensor)
- The Age of Data Affects Accuracy / Correctness of
  - Continuous Quantities
  - Discrete Quantities
- Should Be Considered in the
  - Design of LVC Simulations
  - Analysis of Results
- Result: Manifests Itself as Error

Consistency Model

- Any Notion of Data Quality of Correctness Depends on the Actual Use of the Data
- We are Interested in <u>Accuracy</u> and <u>Timeliness</u> and Their Relationship to Data Values that Change in Real-time (i.e., Temporal Data)
- A Temporal Consistency Model Defines the Correctness of Real-time Data Objects in Terms of Time
- Temporal Consistency Model Relaxes Absolute Consistency by Assigning a <u>Validity Interval</u>

Validity Interval

- Temporal Consistency Theory Assigns a Time Period or Validity Interval, V, to Each Data Object, θ, for which the Value is Considered Correct
- Example:
  - Consider a Data Object, θ, that Represents the Position of an Entity at Time T_0
  - Data Object, θ, Would be Considered Correct Until (T_0+V)
  - Until time (T_0+V), the System is Considered to be <u>Temporally Consistent</u>

What About Error?

- The Amount of Acceptable Error is a Function of Simulation Requirements
- Acceptable Error is Used to Define Interval
- Example:
  - Requirement: Acceptable Error for the Position of an Entity is ± 1 mile
  - Entity Position Max Rate of Change: 60 miles/hour
  - Validity Interval Determined to be 1 minute

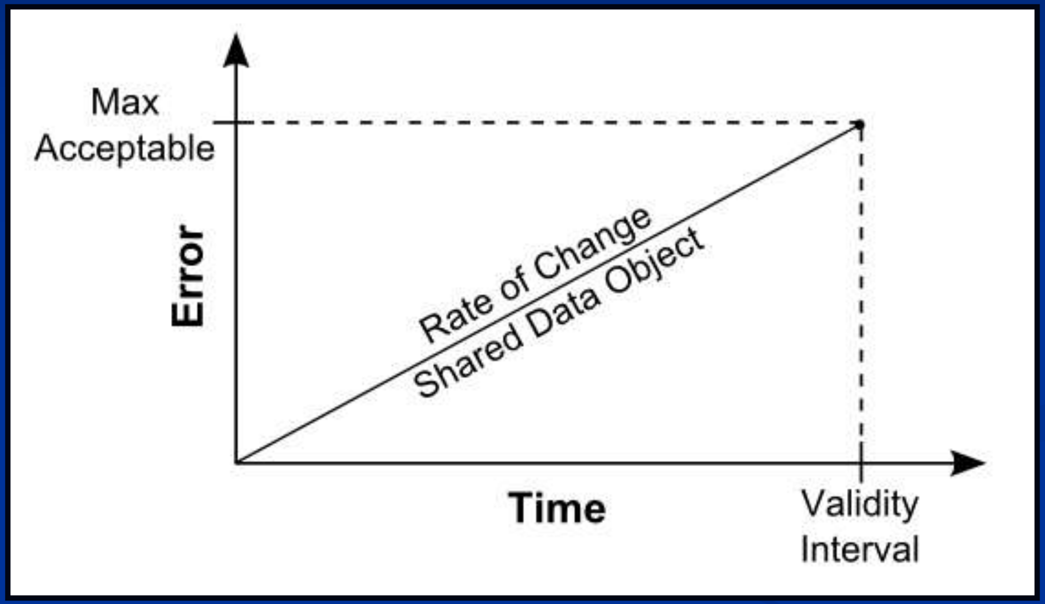
Continuous vs Discrete Data

- Continuous Data
  - Can Use Acceptable Error and Average Rate of Change to Determine Interval
  - Data Quality Focused on <u>Accuracy</u>
- Discrete Data
  - Validity Interval is Not Fixed
  - Data Quality Focused on <u>Timeliness</u>
  - Replicated Data is Simply Incorrect Until Update Received
  - Impact of Temporally Incorrect Discrete State Data Must Be Evaluated

Estimating the Age of Data

- Sources of Inconsistency
  - Simulation/Logical Process Architecture
  - Network Latency
- Example
  - EAAGLES Architecture Characterized
  - Network Latency can be Estimated
- Metrics
  - Determination of Mean Age and Variance of Overall System Design

Application



- To Ensure 95% Temporal Consistency
  - Mean + 1.96 * StdDev $\leq$ Validity Interval

Conclusion

- LVC Simulation Use Inconsistent Data
- Relaxing Absolute Consistency Improves Simulation Performance and Scalability
- Inconsistency is Directly Related to Error
- Acceptable Errors can be Used to Determine Validity Intervals (Max Data Age Tolerated)
- Simulation Systems Should be Carefully Partitioned and Designed to Ensure Correct Operation